TRANSMITTER PRECODING FOR SPACE-TIME CDMA SYSTEM IN MULTIUSER ENVIRONMENT

A Thesis Submitted

In Partial Fulfilment of the Requirements

For the Degree of

Master of Technology

By

Prabhakar Yadav

To the

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

July 2004

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CERTIFICATE

It is being certified that the work contained in the thesis entitled " **Transmitter Precoding for space-time CDMA system in Multi-user environment**" by Prabhakar Yadav has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

23/06/2004

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contents

List of Figures

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I thank all faculty members, who have taught me courses during my Mtech program.

This thesis is dedicated to my family, whose importance I shall not try to put into words. I would like to thank all my friends especially Rathna, Tushar, Pankaj, Ravi, Jawahar, Gopal, Soni and Snehamoy for the help they provided and making my stay at IIT a memorable one.

I thank God for helping me whenever there has been darkness around since my childhood.

Prabhakar Yadav

ABSTRACT

A code division multiple access (CDMA) system has an inherent problem of multiple access interference (MAI) and co-channel interference while fading is a big problem of any communication system. A way to solve the problem of fading was given by Alamouti by introducing the concept of multiple antenna system where diversity is achieved using multiple antennas at the base station as well as at the mobile station.

In this thesis, we have combined together both the space-time block coded and DS-CDMA system and then carried out precoding to reduce the problem of multiple access interference. By using multiple antennas system, we have achieved diversity. Precoding at transmitter end represents a linear transformation of the transmitted signals, such that the mean squared errors at all receivers are minimized. This process of precoding shifts the computational complexity from mobile station to the common transmitter, where it is less critical, thereby reducing the size, power consumption and cost of the mobile station.

In this work, we have first designed a multiple user space-time block coded DS-CDMA system in a fading environment. Then we have designed transformation filter for the transmitter end and compared the system when precoding or linear transformation has been done in single antenna system.

Chapter 1

Introduction:

World-wide cellular systems have undergone rapid changes in the past few decades, and will continue to do so in the future. These changes were manifested in various ways and one of them was the change in multi-access techniques. Primarily, three multi-access schemes have been used from the time cellular systems were deployed. Starting with FDMA in the Advanced mobile phone system (AMPS), the choice became TDMA used along with FDMA (in the Global System for Mobile {GSM} communication standard), now CDMA (CDMA 2000,UMTS) is being favored for use in the next generation of cellular systems.

In recent years, there has been significant research for 3rd generation (3G) wireless communications. Among the various multiple access protocols the wideband direct sequence code division multiple access (DS-CDMA) system has emerged as the main candidate under consideration for UMTS and IMT-2000. Due to expected increase in the traffic in the near future, capacity is one of the critical issues in the design of the mobile communications systems. This is particularly the case in the downlink since new data services like video on demand or Internet browsing tend to be largely asymmetric with higher downstream bit rates.

Multiuser detection techniques [1] have been extensively investigated in order to increase the capacity of spread-spectrum techniques, but these require

somewhat complex algorithms, and their utilization in the downlink demands expensive mobile terminals with higher power consumption, which should be avoided. However Piero Castoldi in his recent book [2] has focussed on low-complexity multiuser detection and interference mitigation techniques to be employed at mobile terminals. It challenges past literature, which suggests that multiuser detection can only be realized at the base station.

Space-time coding is a powerful tool for achieving diversity and coding gain over multi-input multi-output (MIMO) fading channels. The code gain design criteria [3,4] assumes that the transmit and receive antennas are uncorrelated and each element of MIMO channel matrix fades independently. This may not hold true in practice for e.g., in outdoor wireless system, the base station antenna are placed high above the ground and close to each other. In such a scenario, the base station antennas are unobstructed and see no local scatterers leading to high correlation between base station antennas. Recent studies have shown that fading correlations reduce MIMO channel capacity and system performance [5,6]

If the base station before transmission knows the channel impulse response, one can transfer the complexity from mobile unit to the base unit by precoding the transmitted signal such that interference is minimized. Such *a priori* knowledge of channel state information (CSI) is inherently available to the transmitter in time division duplex (TDD) system, in which the uplink and the downlink channels are reciprocal and, hence, the channel estimates obtained

upon reception can be used for precoding in the transmission mode. TDD will be used for instance in the unpaired–band mode of the 3G standard UMTS and diverse precoding technique for TDD system can be found in the literature.

Multi-access techniques are essential in a cellular system because when many users transmit their information, which is overlapping both in time and frequency, over a channel, they can interfere with each other and disrupt any communication that is supposed to be taking place. Using various types of multiple access schemes, the transmitters can be constrained to transmit signals which are orthogonal or quasi-orthogonal to each other to avoid or limit interference. However, this requires code (signature waveform) management via a signalling channel and thus purpose of precoding is lost, which is mainly done to facilitate a reduction of the signalling overhead. Another important application is in military spread spectrum multiple access system where orthogonal spreading is not acceptable. The reason being that we can have only limited number of orthogonal signature waveforms so becomes easy for enemy to detect the information transmitted. Also results in multiuser information theory states that only exceptional orthogonal multiplexing systems achieve the capacity of the channel ([7] and [8]), i.e., non-orthogonal codes are better in terms of approaching the capacity of the channel. Interference in such cases would come by the will of the designer, thus making it a necessary evil. With rapid advances in technology, the fundamental limits of capacity and system performance will become more important

1.1 Organisation of the Thesis

The remainder of the thesis addresses the modelling of space-time CDMA system in a fading environment and then the problem of linear optimisation of the transmitted signals such that the mean square error at the receiver is minimised. This process is also known as Precoding [9]. In Chapter 2, multiuser detection fundamentals and some approaches to solving the multiuser detection problem are included. A mathematical formulation of the problem is also been included. In Chapter **3**, precoding has been discussed in a single antenna system as been done by W.Jang [9,10]. Chapter **4** deals with antenna diversity whereas Chapter **5**, is on the problem of space-time CDMA system modelling and precoding. Chapter **6** gives the simulation results for various systems and finally in Chapter **7**, conclusions are reached and some pointers to further work that is possible in this area.

Chapter 2

MULTI USER DETECTION IN MULTI-ACCESS COMMUNICATION:

The objective of multiuser detection is to detect users in the presence of interference. Such a detector would seek to minimize the multiple access interference. In case of multiuser system, the signals of all users are transmitted at same frequency and at the same time, which can be made possible by allotting different spreading codes to all the users. In case of conventional receivers, the interference is treated as noise but in case of multiuser detection, we can know the structure of interference from other users as the spreading codes of all users are known at the receiver side. This chapter explains the system model of multiuser system and explains the optimal detection, explaining the reason for high computational complexity of the optimal detector.

2.1 SYSTEM MODEL

A very simple model for synchronous baseband transmission and reception is used. An additive white gaussain noise (AWGN) channel model is used. As shown is fig 2.1, the bits of the users are spread by their respective spreading sequences and transmitted over an AWGN channel. This signal, to which white gaussian noise has been added, is fed into bank of matched filters, each matched to the spreading sequence of a different user.

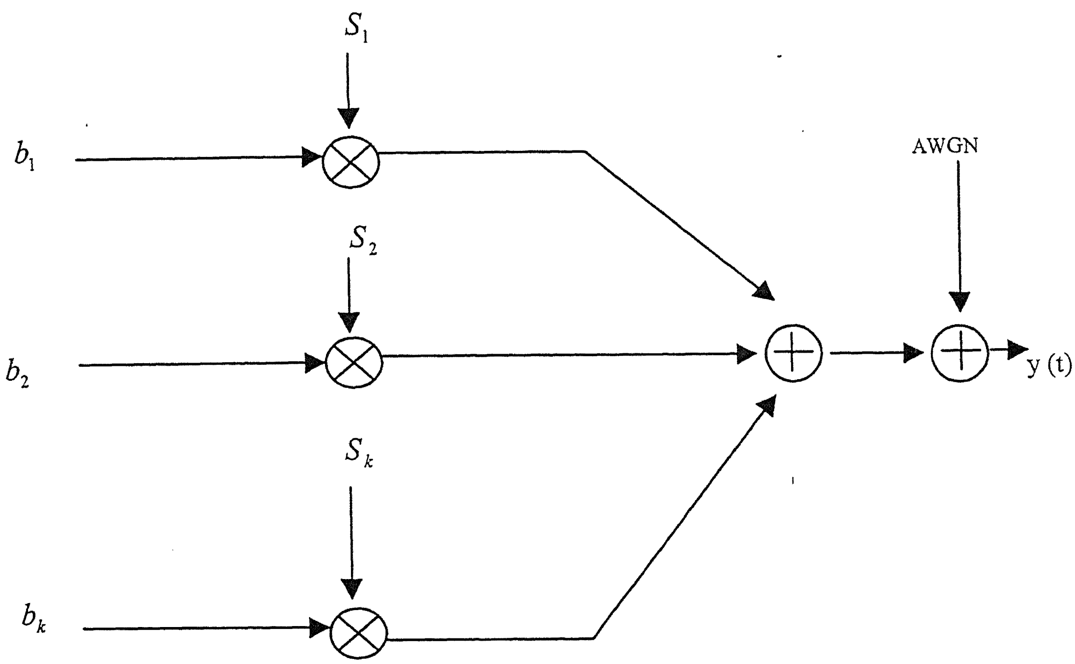

Figure 2.1 Transmitter model

The output of the matched filter is fed into the multiuser detector. The correlation matrix is a matrix whose elements are the correlation values between the spreading waveforms of the users corresponding to the row and the column of a particular element. Finally, the output of the multiuser detector gives the detected bit value. The receiver is shown in fig 2.2. Now the output of the multiuser detector has to be detected in presence of correlated noise, as spreading sequences are non-orthogonal. The optimal method is to go for ML detection but complexity increases exponentially as the number of users increase. So several authors have proposed sub-optimal detection methods like using decorrelator or MMSE detectors, which we will see shortly.

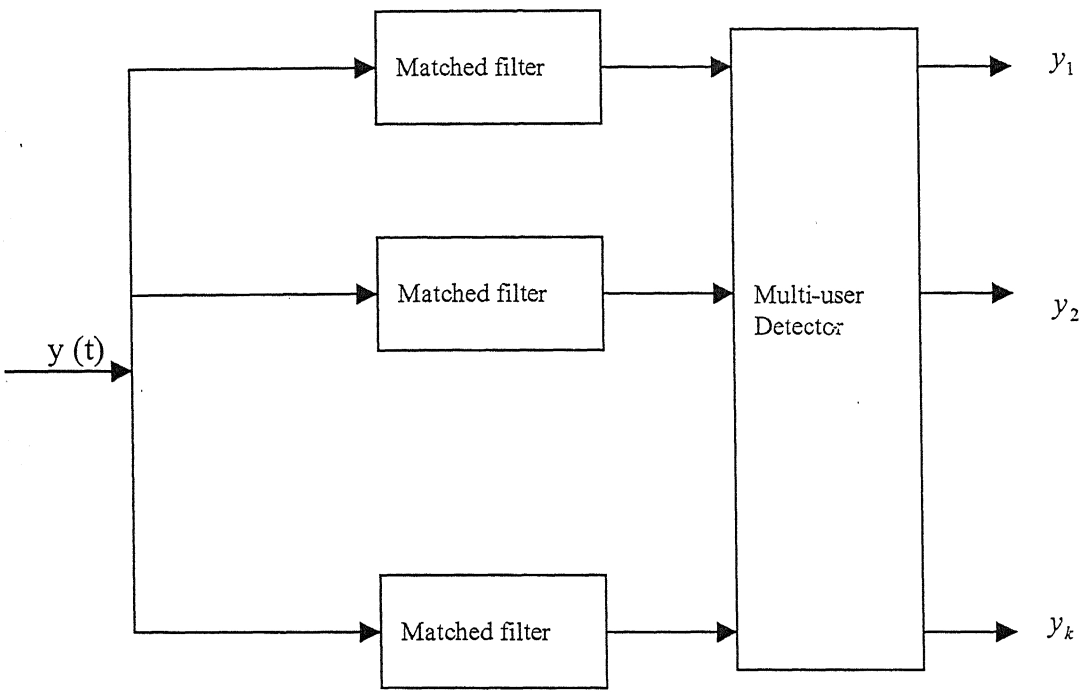

Figure 2.2 Receiver Model

Another important conceptual step is to realise that the orthogonality of the signature waveforms is not imperative for CDMA. For e.g., the performance of the simple correlator considered above will be degraded in the presence of non-orthogonal interfering users, but we may be able to keep the degradation to a tolerable level provided there are not too many or too powerful interfering users. We have infact dropped the requirement that the signature waveforms be orthogonal for the requirement that their mutual interference be sufficiently low. This still requires a careful selection of the signature waveforms so that the cross-correlation are fairly low. Removing the restriction of orthogonal signature waveforms has several benefits that make CDMA an attractive multi-

access technique for many multi-user communication systems. The advantages are:

- The users can be asynchronous, that is, their time epochs need not be aligned and yet "quasi-orthogonality" can be maintained by adequate design of spread spectrum signature waveforms.
- The number of simultaneous users is no longer constrained to twice the duration-bandwidth product of the signature waveforms.
- Sharing of channel resources is inherently dynamic: reliability depends on the number of users, rather than on the (usually much larger) number of potential users of the system. Thus, unlike orthogonal multi-access, it is possible to trade-off reception quality for the increased capacity.

2.2 OPTIMAL DETECTOR

The simple model of the previously discussed model is used for the mathematical derivation of the detector .The received signal is represented as

$$y(t) = \sum_{k=1}^{K} A_k b_k s_k(t) + n(t), \qquad t \in [0, T_b] \qquad (2.1)$$

Where

K is no. of users

A_k is the received amplitude of user K,

b_k is the bit of the user k $(b_k \in \pm 1)$,

$S_k(t)$ is the spreading waveform of user k, such that $\int_0^T S_k(t) = 1$, and

n(t) is the white gaussian noise with unit power spectral density.

T_b is the bit duration.

The output of the bank of matched filter is

$$y_1 = \int_0^T y(t)s_1(t)dt,$$

$$\vdots \qquad (2.2)$$

$$y_k = \int_0^T y(t)s_k(t)dt,$$

(2.2) Can also be written as

$$y_k = A_k b_k + \sum_{j \neq k} A_j b_j \rho_{jk} + n_k \qquad k = 1,\ldots\ldots K \qquad (2.3)$$

Where

$$n_k = \int_0^T n(t)dt$$

is a gaussian random variable with zero mean and variance equal to σ^2, and

$$\rho_{jk} = \int_0^T s_1(t)s_2(t)dt$$

is the correlation between the spreading waveforms of two users. (2.3) can be expressed in the vector form as :

$$\mathbf{y} = \mathbf{RAb} + \mathbf{n}, \qquad (2.4)$$

where **R** is the normalised cross-correlation matrix

$$\text{y} = [y_1, \ldots\ldots\ldots\ldots\ldots, y_k]^T,$$

$$b = [b_1, \dots\dots\dots\dots\dots, b_k]^T,$$

$$A_k = diag(A)_{k \times k},$$

And n is a zero mean gaussian random vector with covariance matrix equal to

$$E[nn^T] = \sigma^2 R \qquad (2.5)$$

The output vector of the bank of matched filter is fed into the multiuser detector, which processes this vector and outputs the bit values of the individual users.

2.2.1 Mathematical Formulation of the Detection Problem:

The maximum *a posteriori* (MAP) detection criterion, which minimises the probability of error, is based on maximising the probability that **b** was transmitted given that **y** is received. Therefore, out of the 2^k possible data vectors, it decides b_i if

$$P(b_i|y) > P(b_j|y), \qquad i \neq j \qquad (2.6)$$

Assuming that the *apriori* probabilities $P(b_i)$ are equal,

$$\begin{aligned} P(b_i|y) &= p(y|b_i)\,P(b_i)/p(y), \\ &= C\,p(y\,|\,b_i), \end{aligned} \qquad (2.7)$$

where C does not depend on the bit vector that is transmitted. To maximise $P(b_i|y)$, the likelihood function $p(y|b_i)$ is to be maximised. Therefore, the maximum likelihood (ML) decision rule becomes:

Decide b_i, if

$$p(y|b_i) > p(y|b_j), \qquad i \neq j$$

Since the noise vector n is gaussian with mean zero and E(y|b) = **RAb**, the *posteriori* probability

$$p(y \mid b) = (1/\pi^k \parallel \sigma^2 R \parallel) * \exp[-(y - RAb)^H (\sigma^2 R^{-1})(y - RAb)]. \qquad (2.8)$$

Therefore the ML decision for **b** is

$$\hat{b} = \arg \max_{b \in \{\pm 1\}^k} \exp[-(y - RAb)^H (\sigma^2 R)(y - RAb)]$$

$$= \arg \min_{b \in \{\pm 1\}^k} b^T Hb - 2b^T Ay, \qquad (2.9)$$

Where **H = ARA** is the unnormalised correlation matrix.

The minimisation in the above equation can be carried out by finding the values of the argument for all 2^k possible values of the vector **b**, and selecting the ones which minimises the argument to be the estimated transmitted vector. It is thus clear that the computational complexity is exponential to the number of users. The detection problem is NP-hard [3] for the general form of the correlation matrix, although for some special cases, it is solvable in polynomial time provided correlation matrix is constrained to have special structure. A non-positive correlation between all pairs of signature waveforms leads to a polynomially solvable case of multiuser detection ([6] and [7]).

2.3 Sub-optimal Multiuser detectors

The detection problem can be viewed as an optimisation problem whose objective function is to be minimised under certain constraints. The function to be minimised is called the objective function and the constraint on **b** defines the constraint set for the problem. The constraint set is also called the decision region. The objective function is convex for positive semidefinite **R,** which is the case in general, and therefore the problem is a combinatorial optimisation problem of a convex function over the corners of a hypercube. There are some standard sub-optimal detectors based on relaxing the constraint set.

2.3.1 Decorrelating Detector:

When the constraint set is fully relaxed to contain the K-dimensional space R^k, The equation (2.9) reduces to a continuous optimisation problem with no constraints [11]:

$$\hat{b} = \gamma\{\arg\min_{b \in R^k} b^T Hb - 2b^T Ay\} \tag{2.10}$$

Where $\gamma\{x\} = +1 \qquad x>0.$

$= -1 \qquad x<0,$

In case $x = 0$, the bit is randomly chosen as +1 or –1. The problem has a unique minimum, because the objective function is convex. The solution to the problem is:

$$\hat{b} = \gamma\{R^{-1}Ay\}. \tag{2.11}$$

The decorrelator is insensitive to different users. It is optimal according to three different criteria: Least squares, Near-far resistance and maximum-likelihood when the receive powers are unknown [1].

2.3.2 MMSE Detector:

The minimum mean square error (MMSE) receiver minimises the mean square error between the actual data sent and the output of the multiuser detector. It is linear detector and has a closed form solution for the output vector. The constraint set is again the hypercube and the estimate of the bits is

$$\hat{b} = \gamma\{A^{-1}(R+\sigma^2 A^{-2})^{-1} y\} \tag{2.12}$$

2.3.3 Generalised MMSE Detector:

The generalised MMSE (GMMSE) was first introduced in [14]. This detector is a result of optimising over the constraint set which is the smallest sphere containing the corners of the hypercube. The problem now becomes:

$$\hat{b} = \gamma\{\arg\min_{b^T b \le K} b^T Hb - 2b^T Ay\}$$

This is again an iterative decoder but has a unique minimum. The unique minimizer of above equation is:

$$\hat{b} = \gamma\{(H+\lambda^* I)^{-1} Ay\} \tag{2.13}$$

where λ^* is the solution of an optimisation problem which is solved iteratively and whose objective function is a rational function of λ. Compared to the MMSE detector, the GMMSE detector is non-linear and does not require knowledge of the variance of noise. It is iterative while MMSE is non-iterative.

Chapter 3

Transmitter Precoding:

Precoding represents a linear transformation of transmitted signals such that the mean squared errors at all receivers are minimized. By means of precoding, the multiuser detection problem is reduced to a decoupled single-user detection problem. The crucial assumption, in fading environment, is that the transmitter knows the characteristics of all channels and that the channel dynamics are sufficiently slow so that fading profiles remain essentially constant over the block of precoded bits.

The original motivation for precoding is to reduce complexity at the receiver end or the mobile station. Researchers have recently begun investigating signal-processing techniques that move computational complexity from the mobile station to the base station, where it can be efficiently managed. Precoding can be applied to any wireless scenario where precoding block size can be made sufficiently small so that the channel appears slow.

3.1 Precoding as addressed before:

[Vojcic/Jang 1998] proposed precoding technique [9] and [10] for multiple access interference cancellation for single antenna system. Precoding is defined as a linear transformation of the transmitted signals such that the mean squared error at each of the receiver is minimized. By means of precoding, the multiuser detection problem is reduced to a decoupled single user detection problem. They did this precoding on a single antenna system in a multiuser

system. The original motivation for doing precoding is to reduce signaling overheads. This is achieved by doing linear transformation of the transmitted signals such that multiple access interference is eliminated, thus, the signal processing complexity is moved to the centralized transmitter and conventional matched filter can be employed in the receiver. However, transmitter precoding tends to increase the transmit power. If the average transmit power is maintained constant, say by scaling down the transmit power of all signals by the same factor, the received signal-to-noise ratio will be reduced correspondingly. Thus, the performance degradation due to multiuser operation is distributed fairly among all users, unlike in most receiver based multiuser detection schemes. For doing precoding following are the requirements:

1. Requires the knowledge of the channel statistics at the transmitter.

2. Slow fading time division duplex (TDD) environment.

3. Requires conventional matched filter receiver or pre-rake in case of multipath.

3.2 Unconstrained optimization:

Consider a synchronous multiuser system with K users sharing the channel with the received signal at the i^{th} receiver given by

$$r_i(t) = x(t) + n_i(t), \qquad 0 \leq t \leq T_b \tag{3.1}$$

Where $n_i(t)$, represents additive white gaussian noise of two sided power spectral density, T_b is the bit duration and $x(t)$ is the transmitted signal specified by

$$x(t) = \sum_{k=1}^{K} A_k s_k(t) b_k$$

$$= S^T A b, \qquad 0 \le t \le T_b \qquad (3.2)$$

Where **s(t)** is the vector of signature waveforms, **A** $= dia(A_i)$ is the diagonal matrix of amplitudes and **b** represents the vector of data bits of K users, such that $b_i \in \{-1,1\}, \vee i \in [1,K]$. It is assumed that signature waveforms have unit energy, that is,

$$\int_0^T S_i^2(t) dt = 1, \qquad i = 1, 2, \ldots\ldots K \qquad (3.3)$$

It is easy to check that the likelihood function depends on the observation only through the outputs of the bank of matched filters matched to the signature waveforms,

$$y_i = \int_0^T r_i(t) S_i(t) dt, \qquad i=1,2\ldots\ldots\ldots k \qquad (3.4)$$

by combining MF outputs from **K** receiving sites into a single vector, $y = \{y_1 \ldots\ldots\ldots\ldots y_k\}^T$, we get

$$y = RAb + n \qquad (3.5)$$

Where R is a positive semidefinite cross correlation matrix with elements $R_{i,j}$ defined as

$$R_{i,j} = \int_0^{T_b} s_i(t) s_j(t) dt \qquad (3.6)$$

and n is a zero-mean gaussian noise vector with covariance matrix equal to $dia\{\sigma^2\}$. To reduce the effect of multiple access interference (MAI), consider

transmitter precoding, defined by linear transformation matrix **T**. Then the transmitted signal is given by

$$x(t) = S^T TAb \tag{3.7}$$

Where **T** is a K×K matrix to be chosen according to some optimality criterion. Therefore, with precoding, the vector of MF output is

$$\mathbf{y=RTAb+n} \tag{3.8}$$

To find **T** we employ the MMSE criterion. Consider now the mean–squared error (cost function) defined as

$$\begin{aligned} J &= E_{b,n}\{\| Ab - y \|^2\} \\ &= E_{b,n}\{\| Ab - (RTAb + n) \|^2\} \end{aligned} \tag{3.9}$$

where E represents expectation (w.r.t.) the noise vector **n** and data vector **b**. The optimum precoding transformation T, which minimizes J, is

$$T = R^{-1} \tag{3.10}$$

Then,

$$\mathbf{Y=Ab + n,} \tag{3.11}$$

Thus, the multi-user problem is decoupled into **K** separate single user detection problems, without the noise enhancement at the receiver, but at the expense of larger transmit energy.

To maintain the average transmit energy with precoding the same as without precoding, we modify the precoding transformation as

$$T = \sqrt{C}\, R^{-1},$$

Where **C** is a power-scaling factor.

But **Vojcic and Jang** in their paper [9] showed that doing constrained optimization at higher SNR gives a better performance then power scaling discussed above.

3.3 Constrained Optimization:

A direct approach to find the optimum T (in the MMSE sense) under average power constraint can be formulated as

$$\min_{T\in R^{k\times k}} E_{b,n}\{\| Ab-y\|^2\}$$

with **y** defined , under the constraint,

$$E_{av}(T)\equiv E_b\{\int_0^{T_b} x^2(t)dt\}$$

$$=\text{trace}\{T^T RTA^2\}$$

$$=\sum_{i=1}^{k} A_i^2 \qquad (3.12)$$

where $E_{av}(T)$ is the total average transmit energy per bit interval with precoding by transformation **T** .

The problem can be easily solved by means of LaGrange multiplier method. Its used when we want to minimize some function under constraint. That is, we want to find T, which minimizes

$$\min_{T\in R^{k\times k}} E_{b,n}\{\| Ab-y\|^2\}+\lambda E_{av}(T). \qquad (3.13)$$

where λ. is the LaGrange multiplier.

An approach to solve the above equation can be seen in the appendix of [9,10] and is given by

$$T = (R + \lambda I)^{-1} \tag{3.14}$$

where **I** is an identity matrix and λ can be found from above equation of constraint and it comes out to be

$$\lambda = \frac{tr[A^2 T^T R(TR - I)]}{tr(A^2)} \tag{3.15}$$

Notice that in above two-equation (3.14) and (3.15), T and λ are functions of each other, thus, suggesting a recursive algorithm to obtain the solution. The same precoding procedure can be applied to frequency selective fading paths.

Chapter 4

Space-time Block Coding:

The next–generation wireless systems are required to have high voice quality as compared to current cellular mobile radio standards and provide high rate data services (upto 2 Mbps). At the same time remote units are supposed to be small lightweight pocket communicators. Furthermore, they should operate reliably in all sort of environment: macro, micro, and picocellular ; urban, suburban and rural; indoor and outdoor. In other words, the next generation systems are supposed to have better quality and coverage, be more power and bandwidth efficient and be deployed in diverse environment.

The fundamental phenomenon that makes reliable wireless transmission difficult is time-varying multipath fading. It is this phenomenon which makes tetherless transmission a challenge when compared to fiber, coaxial cable, line-of-sight microwave or even satellite transmissions. Typically, to reduce a bit error rate from $10^{-2} to 10^{-3}$ may require 1-or-2 dB higher SNR in AWGN channel. Achieving it in multipath may require upto 10-dB improvement in SNR. This improvement in SNR may not be achieved by higher power or additional bandwidth as it is contrary to the requirements of next generation systems. It is therefore, crucial to effectively combat or reduce the effect of fading at both the remote units and the base station, without additional power

If channel conditions as experienced by the receiver on one side of the link are known at the transmitter on the other side, the transmitter can predistort the signal in order to overcome the effect of channel at the receiver. But this has a basic problem that transmitter does not have knowledge about the channel condition except for the case when the system is operating in TDD mode. So in other case, the channel information has to be fed back, which results in throughput degradation and considerable added complexity to both the transmitter and receiver.

Other technique is frequency and time diversity, but have there own problem such as large delays when the channel is slowly varying in case of time interleaving. Equivalently, spread spectrum technique are ineffective when coherence bandwidth of the channel is larger than the spreading bandwidth or, equivalently, where there is relatively small delay spread in the channel.

In most, scattering environments, antenna diversity is a practical, effective and hence, a widely applied technique for reducing the effect of multipath fading. The classical approach is to use multiple antennas at the receiver and perform combining or selection and switching in order to improve the quality of received signal. However, the major problem with receiver diversity is the cost, size, and power of the remote units. The use of multiple antennas and radio frequency (RF) chains makes the remote units larger and more expensive. Hence diversity approaches have widely been applied to base stations to improve the quality of reception.

Alamouti, thus proposed transmit diversity [11], where we can have two transmitting antennas and one receiver antenna at mobile station.

4.1 The New Transmit Diversity Scheme:

Fig(4.1) shows the baseband representation of the new two branch transmit diversity scheme. The scheme uses two transmitting antennas and one receiving antenna and may be defined by the following three functions:

- The encoding and transmission sequence of information symbols at the transmitter.
- The combining scheme at the receiver.
- The decision rule for maximum likelihood detection.

1) At a given symbol period, two signals are simultaneously transmitted from the two antennas. The signal transmitted from antenna zero is denoted by s_0 and from antenna one by s_1.

So the scheme of transmission is as :

	Antenna 0	**Antenna 1**
Time (t)	s_0	s_1
Time(t+T)	$-s_1^*$	s_0^*

The channel at time t may be modeled by a complex multiplicative distortion $h_0(t)$ for transmit antenna zero and $h_1(t)$ for the transmit antenna one. Assuming that fading is constant over two consecutive symbols, we can write

$$h_0(t) = h_0(t+T) = h_0 = \alpha_0 e^{j\theta_0} \tag{4.1}$$

$$h_1(t) = h_1(t+T) = h_1 = \alpha_1 e^{j\theta_1} \qquad (4.2)$$

where t is the symbol duration. The received signals can then be written as

$$r_0 = r(t) = h_0 s_0 + h_1 s_1 + n_0 \qquad (4.3)$$

$$r_1 = r_1(t) = -h_0 s_1^* + h_1 s_0^* + n_1 \qquad (4.4)$$

where r_0 and r_1 are the received signals at t and (t+T).

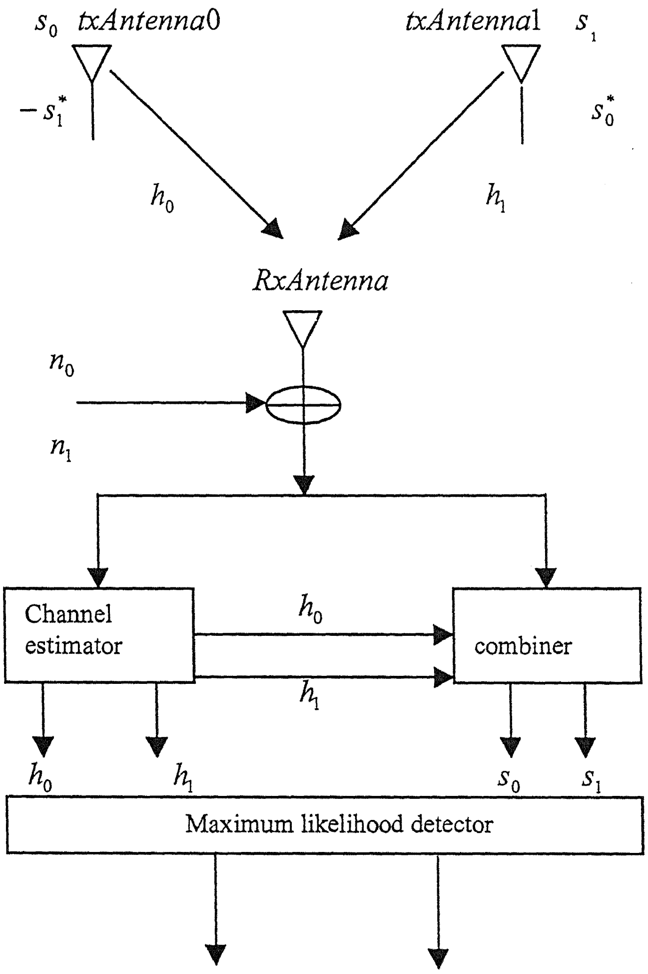

Fig (4.1) The New two-branch transmit diversity scheme with one Rx.

The combiner shown in fig (4.1) builds the following two combined signals that are sent to the maximum likelihood detector:

$$s_0 = h_0^* r_0 + h_1 r_1^* \tag{4.5}$$

$$s_1 = h_1^* r_0 - h_1 r_1^* \tag{4.6}$$

It is important to note that the scheme is different from the MRRC scheme. There we use two or more antennas at the receiver side while only one antenna is at the transmitter side. Substituting the values of channel coefficient from above equation, we get

$$s_0 = (\alpha_0^2 + \alpha_1^2)s_0 + h_0^* n_0 + h_1 n_1 \tag{4.7}$$

$$s_1 = (\alpha_0^2 + \alpha_1^2)s_1 - h_0 n_1^* + h_1^* n_0 \tag{4.8}$$

These combined signals are then sent to maximum likelihood detector which for each of the signals s_0 and s_1, uses the decision rule .The resulting combined signals are equivalent to that obtained from two branch MRRC. The only difference is phase rotations on the noise components, which do not degrade the effective SNR. Therefore, the resulting diversity order from the new two-branch transmit diversity scheme with one receiver is equal to that of two-branch MRRC.

Chapter 5

ON CDMA WITH SPACE-TIME CODES:

We now explore code division multiple access systems over quasi-static flat fading channel. We first propose a technique to obtain transmit diversity for a single user, then proposed scheme is generalized to multiuser system. Transmit diversity appears as a powerful tool to combat the impairments of wireless channels. Tarokh did the generalization of the Alamouti scheme to more than two transmitter antennas where ST block codes from orthogonal design were given. Due to their orthogonal structure, the maximum likelihood (ML) decoding of these codes can be implemented .On the other hand, the conjunction of code division multiple access and ST code is a very interesting approach to combat the impairments of wireless channels [12].

5.1 System model for single user:

Consider a case of two transmitter and one receiver antenna, so applying the Alamouti scheme of encoding and transmission.

Let us suppose that without precoding, r_1 be the received signal during two-time duration and y_1 be the corresponding decision statistics generated by receiver of user 1. Let h_k^t be the fading coefficient between transmit antenna **t** at the base station and receive antenna of user k. so the received signal can be written as:

$$r_1 = H_1 S b + n_1 \tag{5.1}$$

where

$$H_1 = \begin{bmatrix} h_1^1 & h_1^2 \\ h_1^{2*} & -h_1^{1*} \end{bmatrix}$$

$$S = \begin{bmatrix} s_1 & s_2 \\ s_2 & s_1 \end{bmatrix}$$ where s_1 and s_2 are the spreading sequences allotted to the same user.

$$b = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$ are the two bits of say user k.

Now the decision statistics generated by receiver of user1 can be written as

$$y_1 = H_1^H H_1 S_1^T S b + H_1^H n_1 \tag{5.2}$$

Assuming no MAI (i.e. assuming the use of orthogonal signals in a metric channel), the above equation will result into a fine structure of

$$\hat{b}_1 = sign(\mathrm{Re}(y_1)) = \begin{bmatrix} |h_1^1|^2 + |h_1^2|^2 & 0 \\ 0 & |h_1^1|^2 + |h_1^2|^2 \end{bmatrix} \left(\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} + n_1 \right) \tag{5.3}$$

This results from the orthogonality of the columns of H_1 and demonstrates the advantage of STBC.

Now let us model space-time block coded CDMA system for multiuser communication system with K users.

5.2 System model for multiuser communication systems:

We will take two users for modeling multiuser system and final result can easily be extended to K user system.

Let r_i and r_{i+1}^H be the two discrete time received signal at (i^{th}) and ($i+1^{th}$) symbol period. The transmitted baseband signal at one symbol duration for user k at i^{th} symbol period can be written as

$$C_{k,i} = \sqrt{P_k} b_{k,i} S_k, \tag{5.4}$$

where P_k is the transmission power, $b_{k,i}$ is the k^{th} user transmitted data signal with duration T at i^{th} symbol duration, S_k is normalized spreading waveform of user k. The two consecutive symbols to be transmitted of all K users $\{C_{1,i}, C_{1,i+1}, \ldots\ldots\ldots\ldots, C_{k,i}, C_{k,i+1}\}$ are further divided into two groups as $\{C_{1,i}, C_{2,i}, \ldots\ldots\ldots\ldots, C_{k,i}\}$ and $\{C_{1,i+1}, \ldots\ldots\ldots\ldots, C_{k,i+1}\}$ encoded by Alamouti STBC coder and then transmitted simultaneously from two antennas during two symbol period, the signals $\{C_{1,i}, C_{2,i}, \ldots\ldots\ldots\ldots, C_{k,i}\}$ are transmitted through the first antenna and the signals $\{C_{1,i+1}, \ldots\ldots\ldots\ldots, C_{k,i+1}\}$ from the antenna two. Then the STBC encoded signals $\{-C_{1,i+1}^*, \ldots\ldots\ldots\ldots, -C_{k,i+1}^*\}$ are transmitted from antenna 1 and the signals $\{C_{1,i}^*, C_{2,i}^*, \ldots\ldots\ldots\ldots, C_{k,i}^*\}$ from antenna 2 at next symbol duration period.

Assuming a quasi-static channel so as to assume that the coefficient of channel during i^{th} and $(i+1^{th})$ symbol period remain constant and assume flat fading channel. Let the coefficient be h_1 and h_2 from first and second antenna respectively to the mobile station. Assuming the transmission power at each the antennas are same, the discrete–time received signals at i^{th} symbol period for two user can be written as

$$r_i = h_1 b_{1,i} S_{11} + h_2 b_{1,i+1} S_{12} + h_1 b_{2,i} S_{21} + h_2 b_{2,i+1} S_{22} + n_i \tag{5.5}$$

and signal received during ($i+1^{th}$) symbol period can be written as

$$r_{i+1}^{H} = -h_1^{*} b_{1,i+1} S_{12} + h_2^{*} b_{1,i} S_{11} - h_1^{*} b_{2,i+1} S_{22} + h_2^{*} b_{2,i} S_{21} + n_{i+1}^{H} \tag{5.6}$$

Now the received signals are passed through matched filter, having information about the spread sequences of all users. The motivation for using Multiuser detection is that we can know the structure of interference from other users and thus we can successively cancel the interference. Once the received signals are passed through matched filter, we can do the further processing on the lines as suggested by Alamouti in his original paper on antenna diversity [11].

After processing the output of matched filter, we get, which can be represented in vector notation as:

$$y = H^{H} H S^{H} S A b + \hat{n} \tag{5.7}$$

which can be further written as

$$y = H^{H} H R A b + \hat{n} \tag{5.8}$$

where

$$H = \begin{bmatrix} h_1 & h_2 & 0 & 0 \\ h_2^* & -h_1^* & 0 & 0 \\ 0 & 0 & h_1 & h_2 \\ 0 & 0 & h_2^* & -h_1^* \end{bmatrix},$$

$$R = \begin{bmatrix} R_{1111} & R_{1112} & R_{1121} & R_{1122} \\ R_{1211} & R_{1212} & R_{1221} & R_{1222} \\ R_{2111} & R_{2112} & R_{2121} & R_{2122} \\ R_{2211} & R_{2212} & R_{2221} & R_{2222} \end{bmatrix},$$

$$A = \begin{bmatrix} A & 0 & 0 & 0 \\ 0 & A & 0 & 0 \\ 0 & 0 & A & 0 \\ 0 & 0 & 0 & A \end{bmatrix},$$

$$b = [b_{1,i} b_{1,i+1} b_{2,i} b_{2,i+1}]^T,$$

$\hat{n}$, is a zero mean AWGN noise with covariance equal to $\sigma^2 R$.

It can be noticed that the conventional STBC receiver does not eliminate the MAI and co-channel interference, where they are treated as white gaussian noise.

5.3 Space-time Block Precoding Scheme:

With the application of the space-time block coding in CDMA communications, the MAI and co-channel interference is enhanced by multi-antenna transmission and multi-path environment and will severely worsen the system performance. It can be even worse than the conventional single-input-single-output (SISO) antenna system without STBC application especially for heavily loaded systems. Since the uplink and downlink are on the same carrier frequency in TDD link, we can assume that the channel impulse responses in the consecutive uplink and downlink time slots are same. By using this TDD special characteristic, the MAI and co-channel interference cancellation could be carried out by proposed precoding scheme in the base station without the additional modification in the MS.

With the introduction of Precoding matrix **T** at transmitter end, the received signal can be written as :

$$y = R_i TAb + \hat{n} \tag{5.9}$$

where $R_i = H_i^H HR$ and $\hat{n}$ is the AWGN noise ,with covariance matrix equal to $\sigma^2 R$ and **T** is the precoding matrix.

Now we know that when precoding is done, the transmit energy increases. Now we want to constraint the system such that the transmit energy remains constant, so again introduce LaGrange multiplier and carry out optimization.

Let **J** is the cost function. Therefore,

$$J = E_{b,n}\{\| Ab - (R_i TAb + \hat{n}) \|^2\} + 2\lambda tr(A^2 T^T \hat{R} T) \tag{5.10}$$

Now the above equation can be expanded as:

$$J = E_{b,n}\{[Ab - (R_i TAb + \hat{n})]^T [Ab - (R_i TAb + \hat{n})]\} + 2\lambda tr(A^2 T^T \hat{R} T)$$

$$= E_{b,n}\{[b^T A^T - (b^T A^T T^T R_i^T + \hat{n}^T)][Ab - (R_i TAb + \hat{n}]\} + 2\lambda tr(A^2 T^T \hat{R} T) \tag{5.11}$$

Now further expanding the above equation, we get

$$J = E_{b,n}[b^T A^T Ab - b^T A^T R_i TAb - b^T A^T \hat{n} - b^T A^T T^T R_i^T Ab + b^T A^T T^T R_i^T R_i TAb +$$

$$b^T A^T T^T R_i^T \hat{n} - \hat{n}^T Ab + \hat{n}^T R_i TAb + \hat{n}^T \hat{n}] + 2\lambda tr(A^2 T^T \hat{R} T)$$

Now taking expectation w.r.t. to **b** and **n** , we get

$$J = tr(A^2) - tr(A^2 R_i T) - tr(A^2 T^T R_i^T) + tr(A^2 T^T R_i^T R_i T) + E(\hat{n}^T \hat{n}) + 2\lambda tr(A^2 T^T \hat{R} T)$$

Now carrying out the operation $\frac{\partial J}{\partial T}$ and equate it to zero, we get

$$\frac{\partial J}{\partial T} = -R_i A^2 - R_i A^2 + 2R_i^T R_i TA^2 + 2\lambda(2\hat{R} TA^2) = 0 \tag{5.12}$$

$$\Rightarrow 2R_i A^2 = 2R_i^T R_i TA^2 + 4\lambda \hat{R} TA^2$$

$$T = (R_i^T R_i + 2\lambda \hat{R})^{-1} R_i \tag{5.13}$$

Now our next task is to find out λ which can be derived from above equation.

The above equation can be written as:

$$R_i T^{-1} = R_i^T R_i + 2\lambda \hat{R}$$

Multiply the above equation from right by TA and by $(TA)^T$ from the left side we get

$$AT^T R_i T^{-1} TA = AT^T R_i^T R_i TA + 2\lambda AT^T \hat{R} TA \tag{5.14}$$

Taking trace on both the sides, we get

$$tr(A^2 T^T R_i) = tr(A^2 T^T R_i^T R_i T) + 2\lambda tr(A^2) \tag{5.15}$$

We have applied the constraint that transmitted power without precoding is same as with precoding i.e.

$$tr(A^2 T^T \hat{R} T) = tr(A^2) \tag{5.16}$$

Therefore,

$$\lambda = \frac{tr(A^2 T^T R_i (I - R_i T)]}{2tr(A^2)} \tag{5.17}$$

Notice that eq (5.13) and eq (5.17) are defined as a function of each other, thus suggesting a recursive algorithm to obtain the solution. This can be accomplished via the following steps.

1) The transmitter precoding matrix is initialized in an appropriate way maintaining a constant average transmit energy and it has been found that $T = I$ provides fast convergence.
2) The value of T is substituted in eq (5.17) and value of λ is calculated.
3) Again the value of T is calculated by substituting of λ and above steps are repeated until the convergence is achieved.

Chapter 6

Simulation Results:

The precoding technique has been simulated for single antenna and for multiple antenna system under various conditions. Simulation results have been shown for both AWGN and fading channels. The effect of number of users and spreading sequences is studied. The results obtained by precoding have been compared with that of a decorrelator, which works as a optimal detector in a multiuser detection system [1].

6.1 Simulation Parameters

The simulations have been carried out taking Gold sequences of length 7 except for the case when systems has been simulated by increasing the no. of users to 10 where gold sequences of length 31 have been considered. The symbol power of each user has been kept constant at 1dB and signal to noise ratio has been varied to obtain the output bit error rate curve w.r.t. SNR.

In case of synchronous transmission, all users have spreading sequences of identical lengths and transmit coherently. Therefore, it is necessary to consider only a single bit of the user at a time, while forming the correlation matrix and detecting them jointly. For example, while detecting K users, the correlation matrix is of size $K \times K$ while in the case of MIMO multiuser system, say for two users, we transmit two pairs of multiplexed bits alternately from two

different antennas so in a sense, we are decoding four bits, thus we are having a correlation matrix of size 2K × 2K.

Fig 6.1

Fig 6.1 compares the output of a multiuser system when optimum detection has been done with that of sub-optimal detector (Decorrelator) and Precoder. For the simulations, we have taken gold sequences of length seven and the channel is an ideal AWGN channel. Paper by Jojcic and Jang clearly suggests that all three methods should give almost same output.

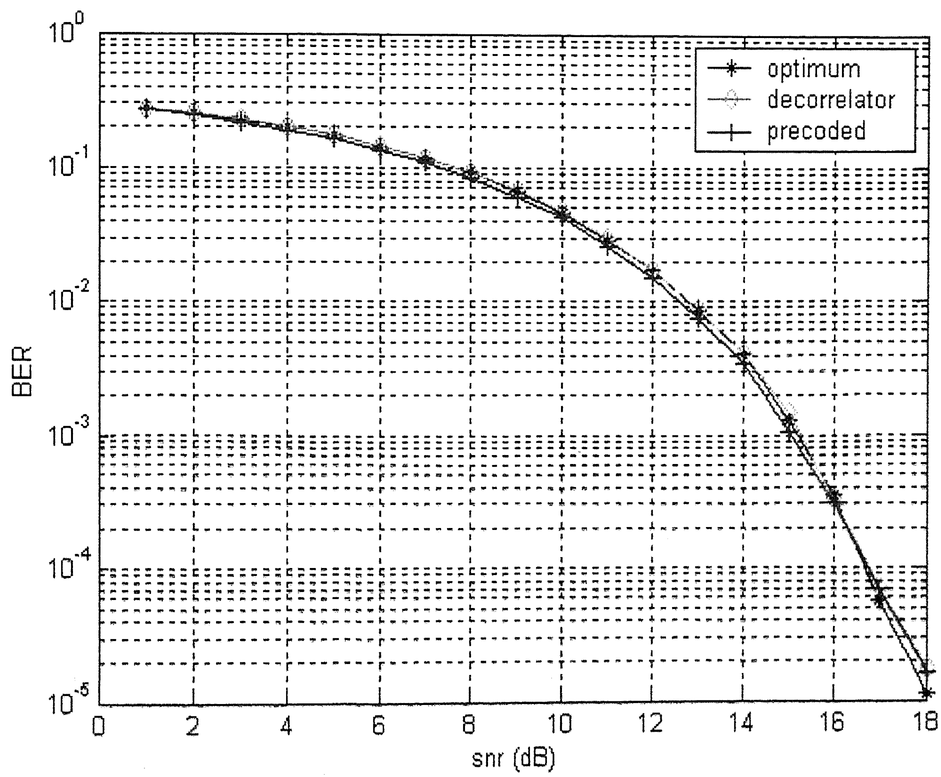

FIG. 6.1 : Comparison of output of multiuser detector using optimal, linear precodeer and sub-optimal detector with K=4 and $A_1/A_2=1$ (i.e. equal power

Fig 6.2

Fig 6.2 shows the effect of increasing number of users on the performance of the system. The output shown is the case when precoding has been done at the transmitter end. The graphs clearly show that as we increase the number of users the performance decreases as interference increases. Here again gold sequences of length seven have been used and the channel is an AWGN channel and it's a single antenna system. Numbers of users taken for comparison are 2, 4 and 7.

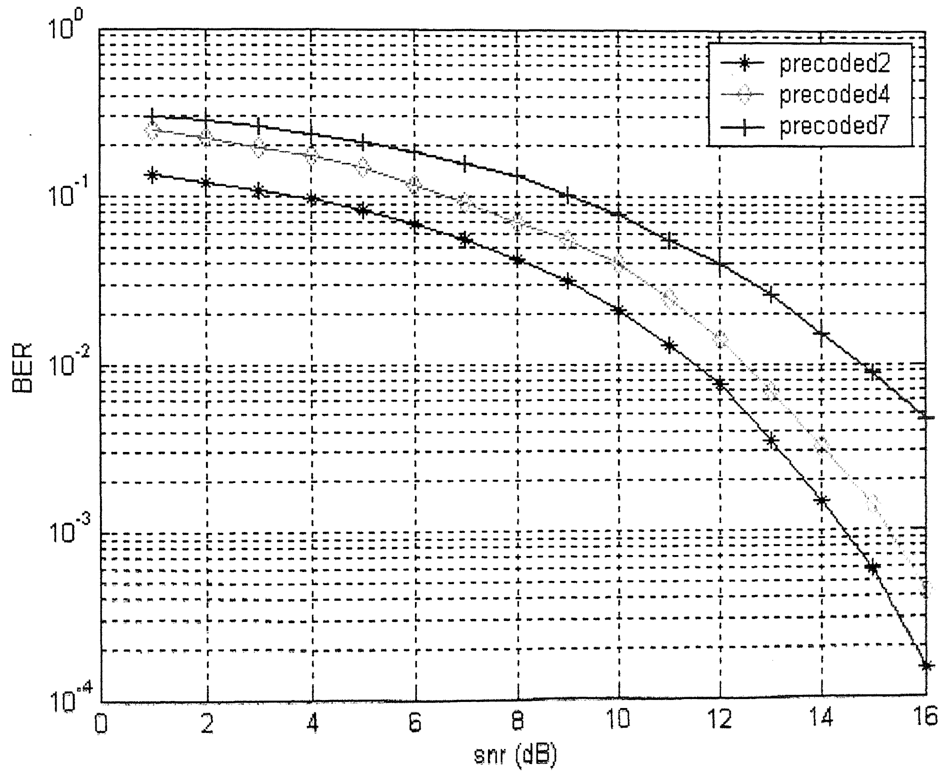

Fig 6.2 shows the performance of a single antenna system for different number of users (K=2, K=4, K=7) and the channel is AWGN. Energy of all users is equal.

Fig 6.3

Fig 6.3 again compares the single antenna multiuser system but in a fading environment. A moderate fading path has been considered where the path amplitudes are between 0.6-0.8 and all bits have equal energy. The output is compared between optimal and sub-optimal detector (Decorrelator) and Precoder. Multiuser system with K=4 has been considered and channel is Raleigh flat fading channel.

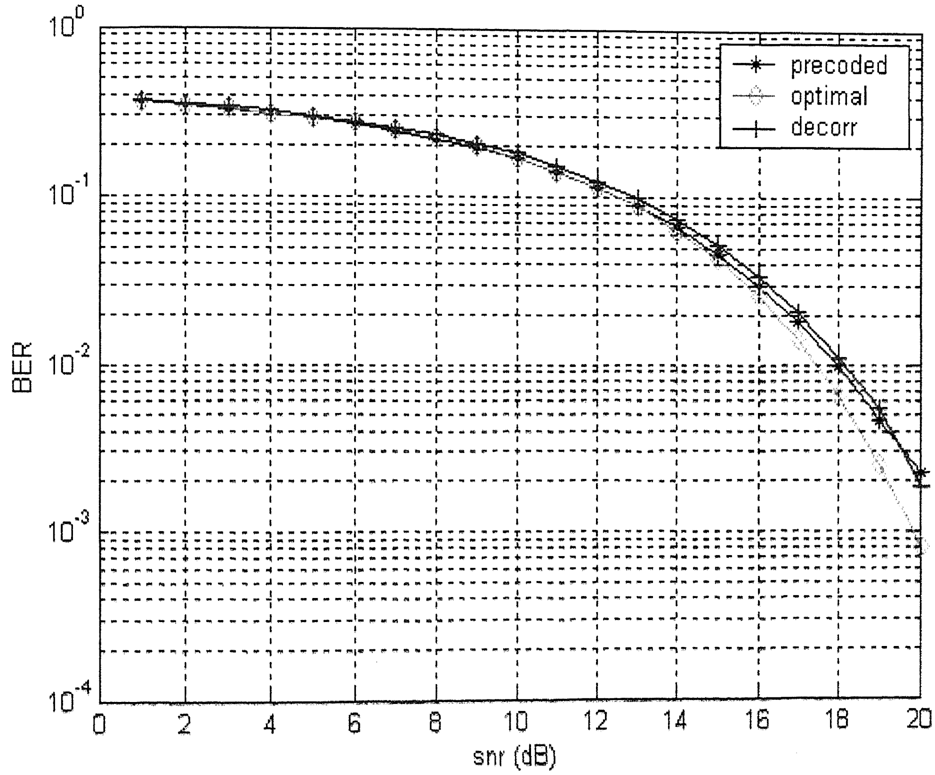

Fig 6.3 Comparison of output of multiuser detector using optimal , sub-optimal detector and linear precoder with K=4 and $A_1 / A_2 = 1$ (i.e. equal power of both users) for a single antenna multiuser system in a moderate fading environment

Fig 6.4

Fig 6.4 shows the precoded output of a single antenna system in different fading environment. The fading environment have been categorized as severely fading channel when path amplitudes are between 0.35-0.55 , moderate faded channel when path amplitudes are between 0 .55-0.75 and third type when coefficients are between 0.75-0.9 again gold sequences of length seven and four user case has been considered. Precoding has been done at transmitter end.

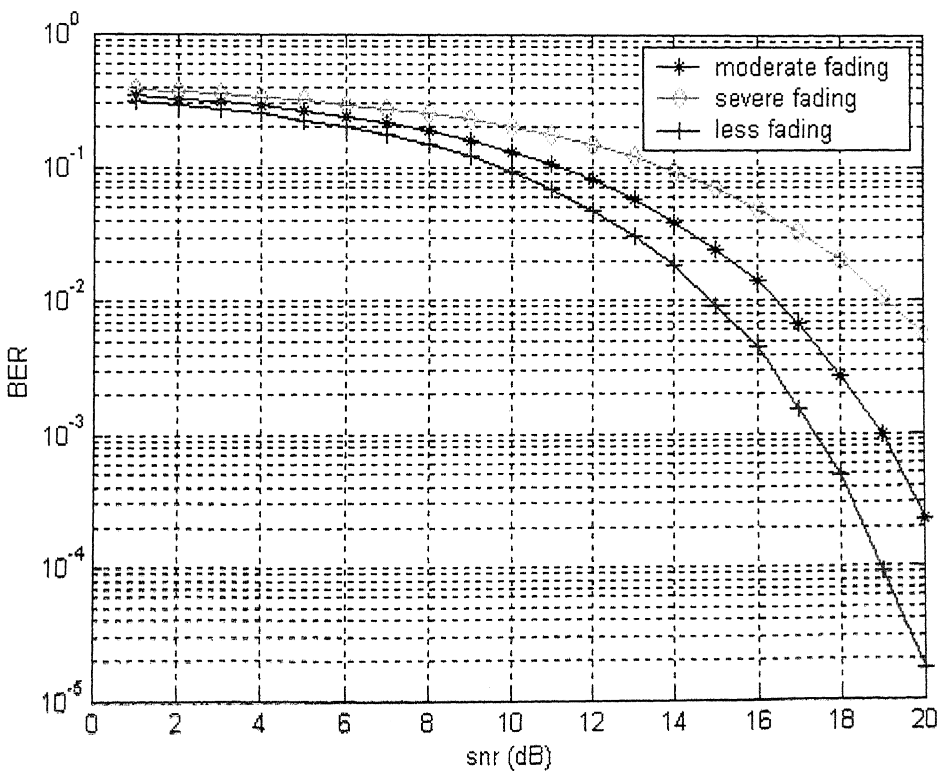

Fig 6.4 shows the precoded output of a single antenna system with K=4 and simulated under different fading environments with $A_1 / A_2 = 1$ (equal energy case).

Fig 6.5

Fig 6.5 shows the output of a MIMO and SISO system under relatively moderate flat fading environment for K=4. The sequences considered are Walsh sequences of length 8. The output clearly shows the advantage that we get out of antenna diversity when using MIMO system. Again all users are having equal energy.

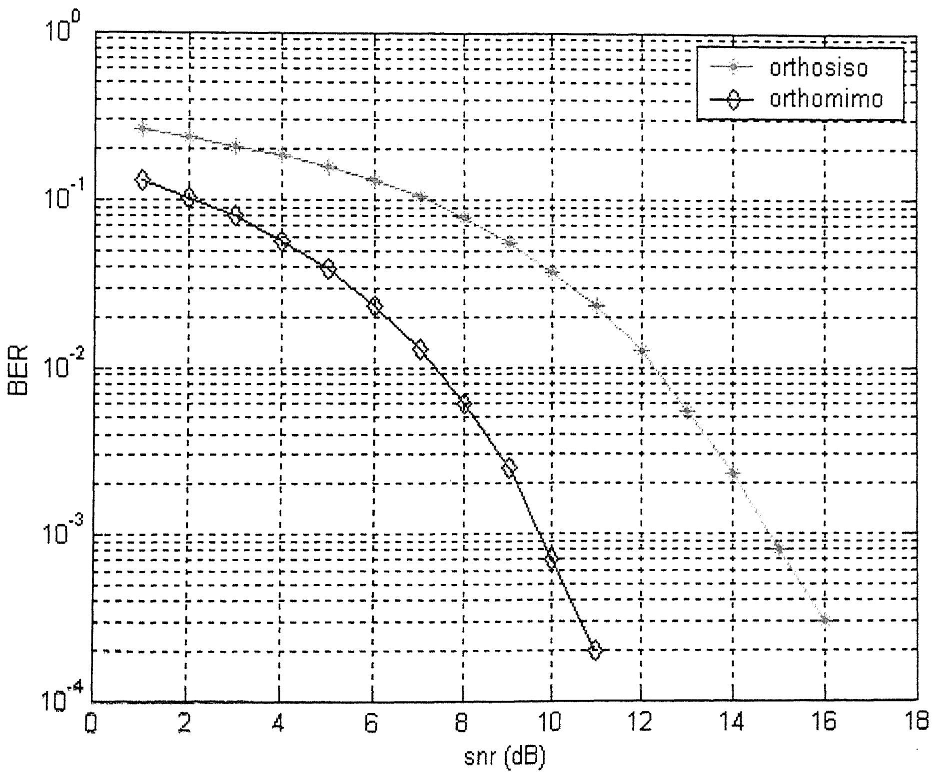

Fig 6.5 shows the output of MIMO and SISO system in a flat fading channel when orthogonal codes are used thus here $\rho_{ij} = 0$ i.e. there is no multi access interference.

Fig 6.6

Fig 6.6 compares the output of precoded MIMO and SISO systems and it clearly shows the advantage we get out of antenna diversity. The simulations have been done in relatively moderate flat fading channel. Here again gold sequences of length 7 have been used and in MIMO system we have applied Alamouti scheme of encoding where two transmit antenna and one receiver antenna has been used. Each user has been allotted 2 sequences each. Precoding has been done at the transmitter side.

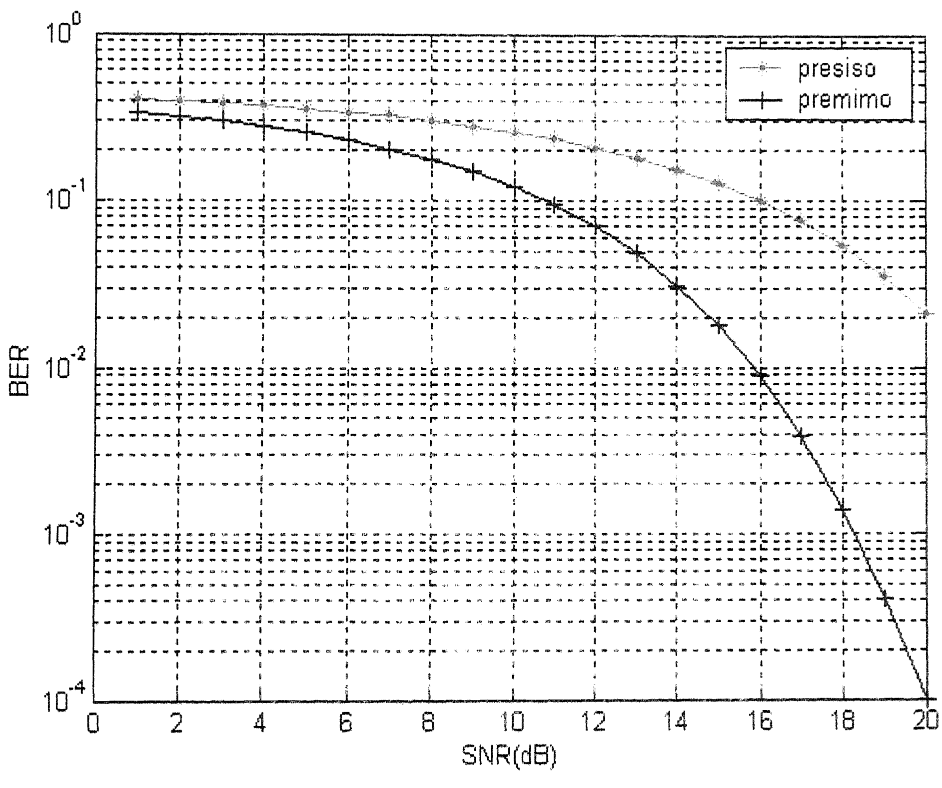

Fig 6.6 compares the output of a precoded SISO and MIMO system in a flat fading channel with K=2, $A_1 / A_2 = 1$ and $\rho_{ij} = 0.14$

Fig. 6.7

Fig 6.7 compares the output of precoded system with that of a decorrelator in a MIMO system. Here we have used gold sequences of length 31 and no. of users is K=10. The channel is a relatively moderate flat fading channel.

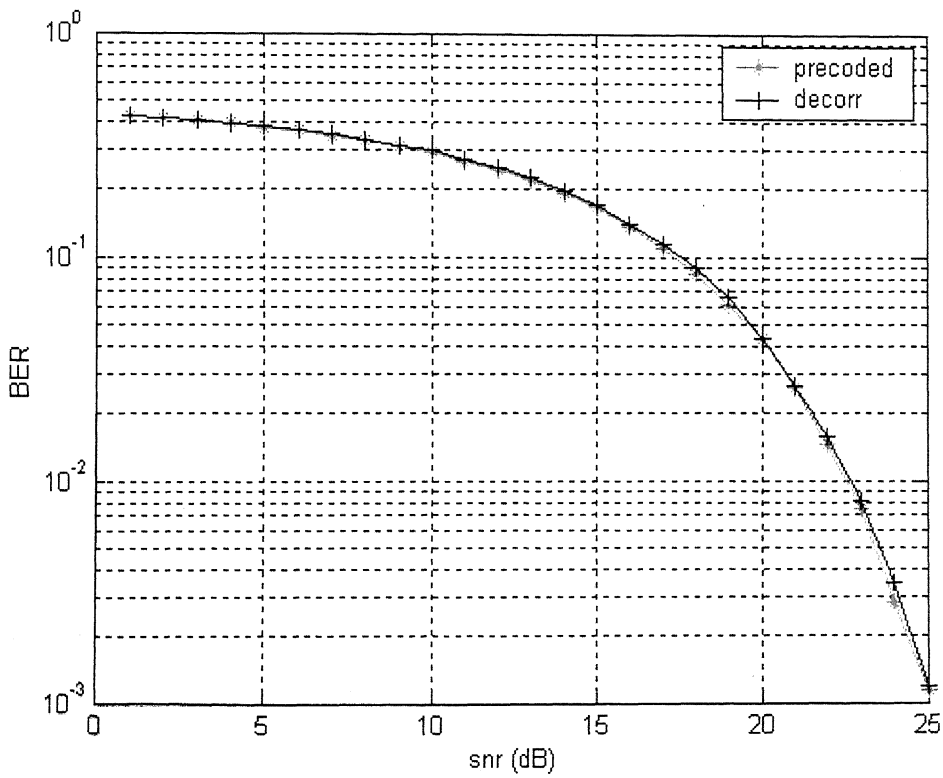

Fig 6.7 compares the output of a decorrelator with that of precoder in a flat fading channel with K=10, $A_1 / A_2 = 1$ and $\rho_{ij} = 0.032$

EFFECT OF PRECODING ON MAI:

Ri =

0.67000	0.09571	0.09571	0.09571
0.09571	0.67000	0.09571	0.09571
0.09571	0.09571	0.67000	0.09571
0.09571	0.09571	0.09571	0.67000

Ri*T =

0.66160	0.02716	0.02716	0.02716
0.02716	0.66160	0.02716	0.02716
0.02716	0.02716	0.66160	0.02716
0.02716	0.02716	0.02716	0.66160

Ri =

0.92800	-0.13257	-0.13257	-0.13257
-0.13257	0.92800	-0.132571	-0.13257
-0.13257	-0.13257	0.92800	-0.13257
-0.13257	-0.13257	-0.13257	0.92800

Ri*T =

0.90186	-0.01720	-0.01720	-0.0172
-0.01720	0.90186	-0.01720	-0.01720
-0.01720	-0.01720	0.90186	-0.01720
-0.01720	-0.01720	-0.01720	0.90186

The above matrices show the effect of precoding. **Ri** shows the normalised correlation matrix while **Ri*T** shows when precoding has been done at transmitter side and its clear from the above two matrices that with the introduction of precoding matrix **T**, the multiple access interference has considerably been reduced. The above simulations were done with gold sequence of length 7 in a flat fading channel.

Future work:

1. Precoding and pre-Rake for n : m case.
2. Precoding for ISI channel, where precoding is done is frequency selective channel making use of orthogonal codes.
3. So far we assumed complete Channel State Information (CSI) at the transmitter, now precoding can be done with only partial CSI.

Chapter 7

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